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Tuned CLC Network For Dual-Active Bridge System

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Abstract: **This paper proposes a resonant dual-active bridge(DAB) converter, which uses a tuned capacitor–inductor–capacitor network. In comparison to the conventional DABs, the proposed topology significantly reduces the bridge currents, lowering both conduction and switching losses and improving the bridge power factors. A mathematical model, which predicts the behavior of the proposed system, is presented to show that both the magnitude and direction of the power flow can be controlled through either relative phase angle or pulse width modulation of voltages produced by the bridges. The viability of the proposed concept is verified through simulation. Experimental results of a 4- kW prototype converter, which has an efficiency of 95% at rated power, are also presented with discussions to demonstrate the improved performance of this topology.**

I. INTRODUCTION

GLOBALLY there has been an increased concern in the unsustainable manner in which we meet our electrical energy needs. Concerns lie mainly in the way that we are depleting natural resources such as oil and gas while polluting the environment as we extract energy from these unrenewable sources. This has resulted in electricity increasingly being generated from renewable energy (RE) sources like wind, hydro, tidal, and solar [1]–[4], to address these concerns. Conventionally, large-scale RE generation plants, such as solar and wind farms, have been built and incorporated into the main grid. Efforts to reduce transmission losses have resulted in a shift toward microscale distributed generation (DG) from RE sources [5]–[7].

Power generation through micro scale distributed RE sources is highly variable in nature mainly due to the dependence of generation on climate conditions [8]. Some form of energy storage is, therefore, an essential and integral part of most, if not all, RE systems to alleviate the mismatch between electricity supply and demand. Electric vehicles (EVs), which initially emerged as an environmentally friendly and efficient means of transport, can also help to provide power network stability in the presence of these fluctuations when used as vehicle-to-grid (V2G) power sources. EV use in RE systems to supplement energy storage, which is referred to as 'Living & Mobility' [9]–[13],

Essentially requires a bidirectional power interface between the local grid and the EV battery to allow for charging the battery when surplus energy is being generated and for extracting energy when there is a deficit. To facilitate a V2G connection with the utility grid requires the use of an ac–dc converter stage, known as a "grid inverter," along with a dc–dc converter, which is also required to be bidirectional. The grid inverter is controlled to maintain a constant dc-link voltage either by extracting power from the grid or delivering power to the grid. When the dc–dc converter is delivering power to the load, the grid inverter functions as a rectifier, whereas when the power flow is reversed it works as

an inverter generating power at grid frequency [14]–[19].Of the many converters developed, both wired and wireless options, dual-active bridges (DABs) are gaining popularity as a preferred option for interfacing EVs with the grid [9]–[15],[18], [19]. DABs facilitate bidirectional power transfer with galvanic isolation, have a high power density and can accommodate a wide range of voltages by operating in both buck and boost modes. Early DAB converters were controlled using single-phase-shift (SPS) control to allow for bidirectional power transfer at variable power levels. SPS control, however, leads to a high reactive current in the system, especially when there is an imbalance in voltages. This high reactive current leads to increased conduction losses in the devices decreasing the overall system's efficiency. Various modulation schemes were investigated in [20]–[30] in an effort to reduce the switch current stresses and the attendant switching and conduction losses. These required a more complicated control system than that used with the conventional SPS control.

Various DAB converters employing a form of series resonance have been investigated, some with phase control and fixed frequency[31], [32], and some with frequency control [33], [34].In a comparison with a fixed-frequency series-resonant DAB variant in [31], the authors concluded that the only advantage of the latter was its lower current distortion, and therefore, reduced eddy-current losses. Also, series resonant DABs typically require a more complex control system, particularly when they are required to operate with wide load and supply voltage variations. All existing DAB converters fundamentally draw a large reactive current component at full power, and therefore, incur large conduction losses. As a solution, this paper presents a novel

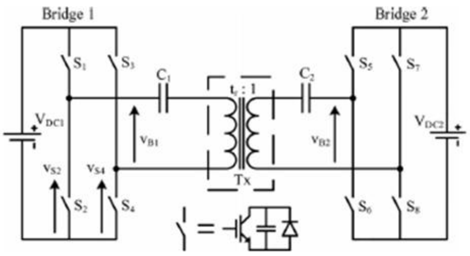


Fig. 1. Proposed resonant DAB converter.

DAB converter topology, which utilizes a resonant network to minimize the reactive power in the bridges. While the proposed converter is conceptually similar to the LCL DAB proposed in [35], including the simple control scheme employed, this variant employs a tuned capacitor–inductor–capacitor (CLC) network, which makes use of the magnetizing and leakage inductances of the isolation transformer. In addition, the response of the CLC network to harmonic voltages produced by the full-bridge converters is significantly different to that of a DAB employing an LCL network.

The tuned CLC network affects a significant reduction in the magnitude of the bridge currents, and therefore, the switching and copper losses. Equal PWM of each bridge is used to control the magnitude of power flow, while the phase shift between the bridges is fixed at 90° or –90°, according to the direction of power flow required. Theoretical analyses as well as simulated results are presented, together with experimental results obtained from a 4-kW prototype system, to demonstrate the ability of the proposed topology to transfer bidirectional power at a high efficiency for a wide range of dc supply voltages and power.

Power electronics is the application of solid-state electronics for the control and conversion of electric power. It also refers to a subject of research in electronic and electrical engineering which deals with design, control, computation and integration of nonlinear, time varying energy processing electronic systems with fast dynamics.

The first high power electronic devices were mercury-arc valves. In modern systems the conversion is performed with semiconductor switching devices such as diodes, thyristors and transistors, pioneered by R. D. Middle brook and others beginning in the 1950s. In contrast to electronic systems concerned with transmission and processing of signals and data, in power electronics substantial amounts of electrical energy are processed. An AC/DC converter (rectifier) is the most typical power electronics device found in many consumer electronic devices, e.g. television sets, personal computers, battery chargers, etc. The power range is typically from tens of watts to several hundred watts. In industry a common application is the variable speed drive (VSD) that is used to control an induction motor. The power range of VSDs starts from a few hundred watts and end at tens of megawatts.

The power conversion systems can be classified according to the type of the input and output power

- AC to DC (rectifier)
- DC to AC (inverter)
- DC to DC (DC-to-DC converter)
- AC to AC (AC-to-AC converter)

Power electronics started with the development of the mercury arc rectifier. Invented by Peter Cooper Hewitt in 1902, it was used to convert alternating current (AC) into direct current (DC). From the 1920s on, research continued on applying thyratrons and grid-controlled mercury arc valves to power transmission. Uno Lamm developed a valve with grading electrodes making mercury valves usable for high voltage direct current transmission. In 1933 selenium rectifiers were invented.

II. PROPOSED RESONANT DAB

The structure of the proposed resonant DAB (RDAB) converter is shown in Fig. 1. There are two full-bridge converters, each of which operates at a fixed switching-frequency fs, and outputs a three-level pulse width modulated voltage source from its dc supply. The bridges are coupled with a resonant network comprising C1 ,C2 , and transformer Tx, which also provides galvanic isolation. Tx has leakage and mutual inductances L1and L2 (see Fig. 3), which are an integral part of the resonant network, which is tuned to the fundamental of the switching frequency, as given by

$$(L_1 + L_2)C_1 = L_2C_2/t_r^2 = \frac{1}{\omega_s^2} = \frac{1}{(2\pi f_s)^2}.$$

An alternative implementation would use a tightly coupled transformer, having minimal leakage inductance, with a discrete inductor in series with the primary. Fig. 2 illustrates the switching sequences used to control the RDAB converter's power flow. All bridge switches are operated with 50% duty at the switching frequency fs, with anti phase switching of the transistors within a leg. A phase displacement

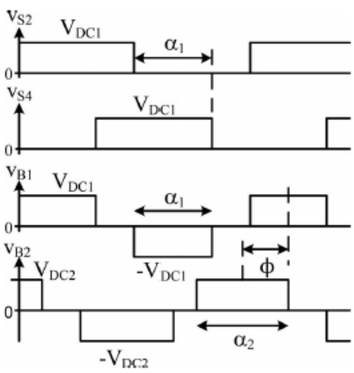


Fig. 2. Bridge voltage waveforms.

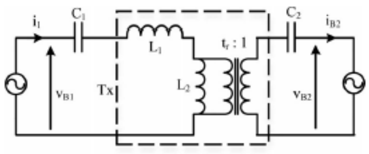


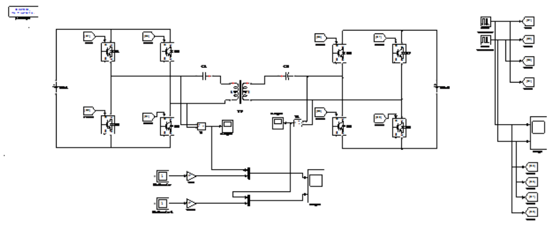
Fig. 3. Initial model.

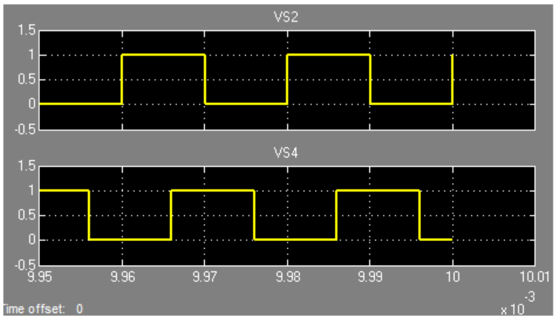
α1between the legs of Bridge 1 is used to affect PWM of its output voltage VB1 , the difference between its leg voltages, as shown in the first three plots. As α1 changes from 0° to180° VB1 's duty changes from 0 to 50%, the latter's square waveform corresponding to 100% modulation. VB2 is obtained from Bridge 2 in a similar manner, using modulation α2. The phase-shift φ between VB1 and VB2 determines the direction of the power flow, and is set to either 90° or −90°, for forward and reverse operation, respectively.

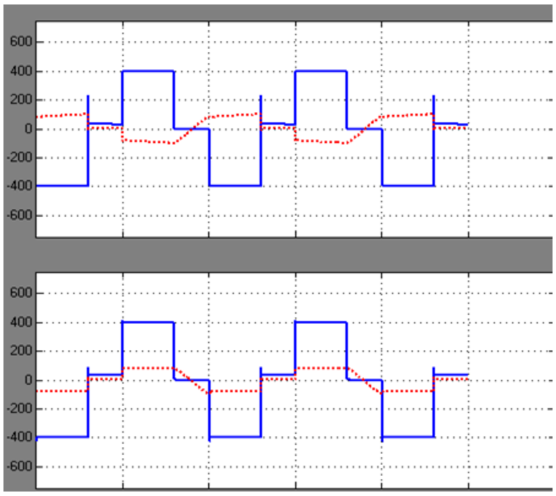
III. RESULTS

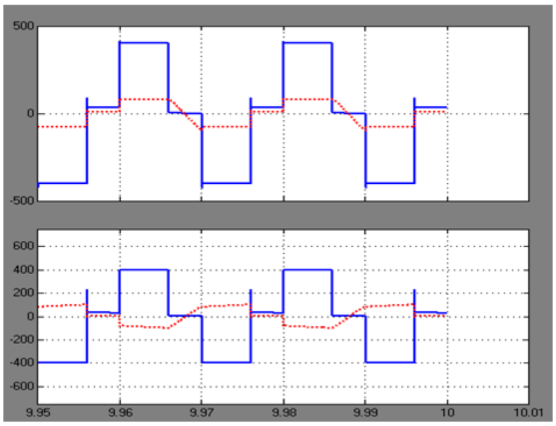
A 4-kW RDAB converter having the parameters given in Table II has been designed and tested to validate the model and the mathematical analysis. Simulation and experimental results are presented here for a range of modulation levels and for forward and reverse power transfers. Simulations were performed with MATLAB in the frequency domain so that the frequency dependent resistances shown in Table III would be included in the calculations. R1 and R2 are the effective resistances at the bridge ports that are they appear in series with C1 and C2 in Fig. 4. In the converter which was built, with the values specified in Table II, a loosely coupled transformer was used to implement L1 as its leakage inductance and L2 as its mutual inductance. Metalized polypropylene capacitors were used forC1 and C2. Control of the bridges was from a fixed gate driver, which generated bridge voltages with equal modulations and with an angle between them of either 90° or −90°, to suite the direction of power transfer. A fixed dead band of 350 ns was used in each leg to prevent cross-current conduction. Initial tests were conducted with each side of the converter connected to a 400-V dc source. The simulated voltages and currents of the proposed system when transferring rated power in the forward direction are shown in Fig. 9. Here, both bridges have the maximum α1 and α2 values of 180°, and Bridge 2leads Bridge 1 by 90°. The experimentally obtained waveforms

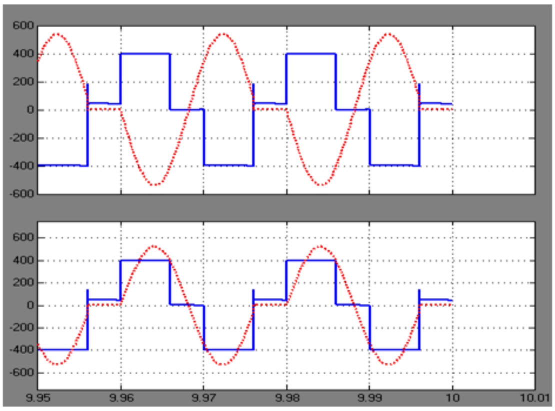
IV. SIMULINK RESULTS AND OUTPUTS











V. CONCLUSION

A novel DAB topology that employs a CLC resonant network has been described. The mathematical model presented has been shown to accurately predict the performance of the

Proposed topology. Although, the RDAB presented in this paper has not been optimized for efficiency, the results of a 4-kW prototype operated under various conditions suggest a significant improvement in performance in comparison to a conventional DAB converter with SPS control. The lower bridge currents of the resonant DAB topology result in an increased power capacity and a higher efficiency over a wide range of bridge dc supply voltages. In comparison with the conventional converter's hardware, the RDAB converter requires the addition of two relatively low-cost capacitors and for these to be tuned with the transformer. As a bonus, these capacitors provide dc current reset, preventing core saturation in the event of abnormal operating conditions. In regard to tuning, it has been shown that the converter's operating characteristics are not particularly sensitive to variations in the component values. There is the potential to further increase the operating efficiency by employing a purpose-designed transformer employing a magnetic shunt to

Affect the required leakage inductance. This transformer will be smaller than that of a conventional DAB converter on account of the lower operating currents.

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